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Age validation of canary rockfish (*Sebastes pinniger*) using two independent otolith techniques: lead-radium and bomb radiocarbon dating.

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ABSTRACT

Canary rockfish (*Sebastes pinniger*) have long been an important part of recreational and commercial rockfish fishing from southeast Alaska to southern California, but localized stock abundances have declined considerably. Based on age estimates from otoliths and other structures, lifespan estimates vary from about 20 years to over 80 years. For the purpose of monitoring stocks, age composition is routinely estimated by counting growth zones in otoliths; however, age estimation procedures and lifespan estimates remain largely unvalidated. Typical age validation techniques have limited application for canary rockfish because they are deep dwelling and may be long lived. In this study, the unaged otolith of the pair from fish aged at the Department of Fisheries and Oceans Canada was used in one of two age validation techniques: 1) lead-radium dating and 2) bomb radiocarbon (^{14}C) dating. Age estimate accuracy and the validity of age estimation procedures were validated based on the results from each technique. Lead-radium dating proved successful in determining a minimum estimate of lifespan was 53 years and provided support for age estimation procedures up to about 50-60 years. These findings were further supported by $\Delta^{14}C$ data, which indicated a minimum estimate of lifespan was 44 ± 3 years. Both techniques validate, to differing degrees, age estimation procedures and provide support for inferring that canary rockfish can live more than 80 years.

Additional keywords and phrases: radiometry, carbon-14, radium-226, lead-210, Scorpaenidae, age estimation, accelerator mass spectrometry, alpha-spectrometry

INTRODUCTION

Canary rockfish (*Sebastes pinniger*), a member of the family Scorpaenidae, is one of at least 65 species of rockfishes found in the northeastern Pacific Ocean (Love et al. 2002). It ranges from southeastern Alaska to northern Baja California, Mexico, with the center of abundance from central California to British Columbia, Canada. The depth range extends from the surface to about 800 m, with most adults residing between 80 and 200 m (Love et al. 2002). The canary rockfish has long been an important part of the rockfish fishery with records of a commercial fishery off Washington and San Francisco, California dating to the 1880s (Love et al. 2002). It is typically caught in commercial trawl and hook-and-line fisheries from Monterey, California to British Columbia, Canada and is often taken with other members of the genus in assemblages that are regionally defined (Yamanaka and Kronlund 1997, Bloeser 1999). The species is an important component of the recreational fishery throughout its range (except B.C., Canada), but declines in abundance led to significant harvest restrictions (i.e. California Department of Fish and Game: Sportfishing Regulations and Pacific Fishery Management Council: 2003 Groundfish Management Regulations). Canary rockfish was classified as overfished in 2000 based on the 1999 assessment (Methot and Piner 2002). A recent stock assessment of the canary rockfish fishery for the west coast of the USA indicated that the estimated depletion level of the spawning biomass in 2005 was between 6% and 11% (Methot and Stewart 2005); this is relative to estimates of unfished levels dating back to 1916 because of the long fishing history.

The targeted canary rockfish fishery off British Columbia, Canada is more recent; however, landings of rockfish were not recorded to species until the late 1960s and the Canadian stocks were likely exploited with other rockfishes as early as the 1950s (Stanley 1999). Landings have been consistent since 1967, but the status of Canadian stocks is poorly known. Management in British Columbia treats canary rockfish fishery as two stocks, a central (Queen Charlotte Sound) and a southern (west coast of Vancouver Island) stock, with two-thirds of the landings traditionally coming from the southern stock. A documented decrease in mean age-at-capture based on the age composition of catches may indicate fishery exploitation has had a significant impact, but there are no convincing signs of over-exploitation. It is possible that stocks are close to maximum exploitation, but the actual status of the canary rockfish fishery for the waters of British Columbia is not well known (Stanley 1999).

Because management decisions are often made from age-based information, it is important to validate age and lifespan estimates as well as the age estimation procedures. Recent work using growth zone counting in otolith thin-sections provided estimates of lifespan for the canary rockfish from about 60 to more than 80 yr (Chilton and Beamish 1982, Boehlert and Yoklavich 1986, Crone et al. 1999, Stanley 1999). Using the otolith burnt section technique (Figure 1; MacLellan 1997), the Department of Fisheries and Oceans Canada (DFO) Ageing Lab in the Pacific Biological Station at Nanaimo, British Columbia has performed routine canary rockfish age estimations for more than a decade and was responsible for the oldest estimated age of 84 yr. Earlier studies estimated lifespan at little more than 20 yr (Phillips 1964, Westrheim and Harling 1975, Six and Horton 1977, Boehlert 1980), but this discrepancy can be explained by earlier studies using whole otoliths versus break-and-burn or sectioned otoliths (Boehlert and Yoklavich 1984). It is increasingly common to find that life-span estimates have increased for rockfishes with advances in otolith ageing and validation techniques (Cailliet et al. 2001).

Age validation techniques that can be applied to deep water fishes range widely in efficacy and age precision (Campana 2001). Some rely on establishing a temporal context to early growth by measuring changes in otolith zones or fish length (e.g., marginal increment analysis and length frequency analysis); however, these techniques require an extrapolation of the age and growth information to older fish because of a loss of zone or length resolution. Other methods rely on marking and recapturing older fish (e.g., oxytetracycline injection and/or tagging), but deep-water, physoclistic fish usually have problems with survival upon return due to barotrauma and the techniques suffer because of low returns. Advances in the use of both naturally occurring and anthropogenic radioactive proxies for age have provided opportunities for independent age validation of deep water fishes. The two primary techniques in use are lead-radium dating and the bomb radiocarbon (^{14}C) chronometer.

Lead-radium dating relies on the incorporation of naturally occurring radium-226 (^{226}Ra) from the environment into the otolith and its subsequent decay to lead-210 (^{210}Pb). By measuring the disequilibria of these two radioisotopes in otolith core material (first few years of life), an independent estimate of age can be determined based on the known ingrowth rate of ^{210}Pb from ^{226}Ra (Campana et al. 1990, Smith et al. 1991, Kimura and Kastelle 1995, Francis 2003). This technique works well as a tool for determining the validity of age interpretations that differ considerably, but its application is limited by relatively low resolution at ages approaching 100 years. The typical end result for this kind of study is that it provides strong support for a given age estimation technique and establishment of an independent estimate of lifespan that supports one age estimation technique over another. For example, lead-radium dating performed on the yelloweye rockfish (*S. ruberrimus*) provided support for age exceeding 100 yr (Andrews et al. 2002).

Use of the bomb ^{14}C chronometer requires a series of individual otoliths for which the birth years, based on standardized growth-zone age estimates, range from a time prior to significant atmospheric testing of thermonuclear devices (pre-1957) to the post-bomb period. This approach utilizes the discrete rise in ^{14}C from atmospheric testing as a time specific marker for age validation. It is the agreement of the bomb ^{14}C record, from the species with age in question, with a reference bomb ^{14}C time-series that becomes a form of age validation. Hence, the utility of this approach for determining age or lifespan is dependent upon the difference between the collection year and time of first rise in ^{14}C for the reference time series. For example, a minimum lifespan of 30 to 38 years was determined for the red snapper (*Lutjanus campechanus*) based on these principles (Baker and Wilson 2001). In addition, age can also be determined by projecting measured ^{14}C levels back to a reference time series (Campana 1997, Andrews et al. 2005) or a series of samples with different collection years and ages can be selected to validate age estimation procedures for a range of age classes younger than the minimum lifespan (Piner and Wischniowski 2004).

Successful application of lead-radium dating and the bomb radiocarbon chronometer to rockfishes (family Scorpaenidae) has a well developed history. The first application of lead-radium dating to otoliths in general was an age validation study on the splitnose rockfish (*S. diploproa*) in which a 60 yr lifespan was supported for the growth-zone age estimation criteria (Bennett et al. 1982). Since this pioneering application, the technique has been applied to several other rockfishes with varying degrees of age resolution (Campana et al. 1990, Kline 1996, Kastelle et al. 2000, Andrews et al. 2002, Stevens et al. 2004, Andrews et al. 2005, Watters et al. 2006). For the bomb radiocarbon technique, its application to fish otoliths began with fishes in the southern hemisphere (Kalish 1993, Kalish 2001), followed by a series of studies in the northern hemisphere (e.g., Campana 1997, Kalish et al. 2001).

The first application of the bomb ^{14}C technique to rockfishes was a follow-up study to age validation work on yelloweye rockfish (Andrews et al. 2002). Because yelloweye rockfish were relatively easy to age from growth zone counts (CV = 4%) and lead-radium dating provided support for the age estimation procedures, a series of yelloweye rockfish otoliths were used to establish a bomb radiocarbon chronometer for the northeastern Pacific Ocean (Kerr et al. 2004). The chronometer established by Kerr et al. (2004) was further corroborated by an independent study of juvenile Pacific halibut (*Hippoglossus stenolepis*) from a similar region (Piner and Wischniowski 2004). These records subsequently provided an independent chronometer for age validation of the quillback (*S. maliger*; Kerr et al. 2005) and bocaccio (*S. paucispinis*; Andrews et al. 2005) rockfishes. A recent application of this technique to canary rockfish collected off Oregon, and aged by the Oregon Department of Fish and Wildlife, provided unexpected results that were attributed to some combination of age estimate bias and regional oceanography (Piner et al. 2005).

The purpose of this study was to assess the validity of age estimates and age estimation procedures used in routine age assignments of canary rockfish by the DFO, along with any agency that utilizes the same age estimation criteria (MacLellan 1997). Lead-radium dating and bomb ^{14}C analyses will be used to provide a basis for support or dispute of canary rockfish age estimates determined using the break and burn method. These results will also be compared with recent findings from a canary rockfish age validation study for collections made off Oregon (Piner et al. 2005). Additionally, variation in regional pre-bomb ^{14}C values for the northeastern Pacific Ocean was examined along with the potential influence of this variability on age validation.

MATERIALS and METHODS

The high estimated lifespan and the availability of a well developed otolith archive at DFO made the canary rockfish an excellent candidate for a combined application of the two independent age validation techniques. Otoliths were selected from these archives based on the criteria for each technique. The lead-radium dating required groups of otoliths and the bomb radiocarbon technique required only a series of carefully chosen otoliths with estimated birth dates spanning the pre-bomb to post-bomb period. The application of each technique was treated as an independent project and is separated into sections for clarity.

Lead-radium dating

Otoliths were selected for analysis from more recent years between 1990 and 1998 based on the number of aged fish available. Age groups were chosen to cover a wide range of estimated age and the groups were as close to a single age as possible. The size of the core material extracted was determined based on 33 whole juvenile otoliths aged at 3 years. Average size of the otoliths was 9.0 mm L x 4.8 mm W x 1.2 mm T and the average weight was 0.073 ± 0.012 (SD) g. This target core size could be easily extracted and consisted of just a few years of growth to minimize the possible error associated with variable ^{226}Ra uptake (Francis 2003). Otoliths from adult fish were ground down to the target core size using a lapping wheel and 80 to 120 grit silicon-carbide paper. The radiometric analysis of the pooled otolith core samples for ^{210}Pb and ^{226}Ra followed procedures previously described in Andrews et al. (1999a & b, and 2005).

Measured ^{210}Pb:^{226}Ra activity ratios for each age group, along with total sample age (growth-zone age plus time since capture), were plotted with the ^{210}Pb:^{226}Ra ingrowth curve to provide a reference to the ratio that would be expected for a given age. The uncertainty for the growth-zone derived age of each group was represented by the age estimate CV (5.8%), as was determined from the variability of age estimates among three readers at DFO. This uncertainty was assigned to the mean age of each group as some indication of what might be the limit for the degree of precision in the age estimation criteria, and should not be confused with the degree of accuracy. Agreement between radiometric age and growth zone derived age was determined by comparing the limits of 95% confidence with the ingrowth curve. To provide a lower limit on the minimum lifespan for the fish aged in this study, the 95% CI from the ^{210}Pb:^{226}Ra ratios provided a validated basis for such a determination.

Bomb radiocarbon

Otoliths from aged canary rockfish were selected from the DFO archive based on estimated birth date to cover the pre-bomb to post-bomb period. Most of the fish specimens that provided the otoliths were captured off the west coast of Vancouver Island. Otoliths used in the radiocarbon part of this study were from three "Major Areas" used for landings record keeping from off British Columbia by DFO (3C-D and 5A-B). The most important samples for recording the rise in ^{14}C (1950-1967) were all from Major Area 3D. The other samples were from Major Areas nearby: 1945 (5A), 1969 and 1973 (5B), and 1980 (3C).

The core of each otolith, which constituted less than the first year of growth, was analyzed for Δ^{14}C because it is known that at least the first year's growth was formed while the fish inhabited the ocean mixed layer. The bomb radiocarbon technique is most reliable for fishes that inhabit the mixed layer of the ocean, at least during a portion of their life history, because of uncertainty regarding mixing rate at depth and limited data on the $\Delta^{14}C$ signal in deeper waters (Kalish 2001).

The size of the core material extracted was determined from nine whole juvenile otoliths with an age of one year. Average dimensions were 6.9 mm L x 3.8 mm W x 0.9 mm D with a weight of about 0.02 g. Sampling within these dimensions was targeted to avoid the inclusion of material formed later in life. Core extraction was performed using a milling machine with a 3.2 mm (1/8") diameter end mill, pressed into the otolith to a depth of 0.8 mm. Visual alignment of the milling machine bit with the center of the distal side of the otolith allowed for correction due to individual variability; the first year's growth was easily recognizable because more recent accretion on the distal surface was negligible. Coring produced small powdered samples that were weighed to the nearest 0.1 mg. For $\Delta^{14}C$ analysis, otolith calcium carbonate ($CaCO_3$) was converted to graphite and measured for ^{14}C content on an accelerator mass spectrometer (AMS) at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California, USA. The ^{14}C measurements were reported as $\Delta^{14}C$ values and a measured $\delta^{13}C$ value of -3.1, similar to marine carbonates, was used in calculating the $\Delta^{14}C$ values, (Stuiver and Polach 1977).

The $\Delta^{14}C$ values measured in the canary rockfish otolith cores were plotted with respect to the estimated birth year, which was estimated based on the difference between estimated age and the collection year. For each birth year a range of uncertainty between readers was calculated based on the age estimation CV (5.8%). This uncertainty was assigned to the birth years as some indication of what might be the limit for the degree of precision in the age estimation criteria, and should not be confused with the degree of accuracy. Agreement of the estimated birth year range with the reference time-series, coupled with use of the exponential fit method, as suggested in Kerr et al. (2004), was used as a basis for providing a minimum lifespan and age estimate accuracy. Specifically, the first sample below the 2 SD criterion of pre-bomb $\Delta^{14}C$ levels was used to determine a minimum lifespan. The reference-time series used for comparisons were from yelloweye rockfish (*S. ruberrimus*; Kerr et al. 2004) and Pacific halibut (*Hippoglossus stenolepis*; Piner and Wischniowshi 2004) because of the regional similarities to the canary rockfish collection locations and specifically yelloweye rockfish for the similarities in life history.

RESULTS

Lead-radium dating

Twelve samples, representing groups of otoliths, were analyzed from fish that ranged in growth-zone derived age from 3 to over 50 years (Table 1). Typically, numerous otoliths are required to attain enough material for measurable ^{210}Pb and ^{226}Ra from the age groups, resulting in a wide age range for ages with low sample availability. For the first set of four samples (CR1-CR4) the target number was about 20 otolith cores because levels of ^{210}Pb and ^{226}Ra were unknown. Once preliminary findings indicated less material was needed, fewer otolith cores were pooled to narrow the estimated age range for the rest of the samples. Fish length ranged from about 20 cm FL for the juvenile groups (CR1 and CR10) to more than 50 cm FL for the older age groups. Collection years varied considerably (1990 to 1998) because otolith age groups were selected based on the number of otoliths available and narrowness of age range for the groups. For most groups the collection dates were all within a few months of each other. Sexes were not separated because validation of the age estimation method was the goal. Total numbers of otoliths per age group ranged from five to twenty and most were male.

Radiometric analysis of all age groups (n = 12) resulted in the successful determination of ^{210}Pb activities, and limited success for ^{226}Ra activities (Table 2). Activities of ^{210}Pb were variable as expected and typically increased with estimated age. No recovery of ^{226}Ra in the first set of four samples was due to a mistake in the mixing of acid that led to changes in the elution characteristics and a loss of radium. Radium was recovered for all other samples (n = 8) and resulted in a variable range of activity (range of 0.0803 to 0.122 dpm g^{-1} (disintegrations per minute per gram). This degree of variability precluded the determination of a radiometric age for the samples where radium was lost because levels were not consistent enough to use an average (0.0988 ± 11% 2SE). Although the activity levels for both ^{210}Pb and ^{226}Ra were quite variable, the ^{210}Pb:^{226}Ra activity ratio increased as expected with growth-zone derived age. The importance of sample-specific ^{226}Ra activity for this species was exemplified by the 3 yr age group (sample CR10), which had the highest measured ^{226}Ra activity in this study and, as expected because of the young age, the lowest ^{210}Pb:^{226}Ra ratio.

The measured ^{210}Pb:^{226}Ra ratios were largely in agreement with the ingrowth curve (Figure 2). All but two samples (CR9 and CR11) were in agreement with growth-zone derived age based on the 95% CI from the measured ratios. To give an indication of the affect of growth-zone ageing bias, the plot included two ingrowth curves that incorporate an age overestimation bias of 25% and 50%. The agreement between growth-zone derived age and ^{210}Pb:^{226}Ra ratios provide support for the age estimates and age estimation procedures.

Radiometric ages determined for the eight samples from which radium was recovered ranged from 3 to 71 years (Table 3). These ages were corrected for time since collection based on the difference from the date of processing and average collection date for the age group. Greater radiometric age uncertainty for the oldest samples was because of the asymptotic nature of the ingrowth curve; small changes in the measured ratio become large changes in radiometric age as the ratio approaches 1.0. By treating lead-radium dating as an independent estimate of age, there was 95% confidence that the oldest canary rockfish used in this study were at least 53 years of age (CR11).

Bomb radiocarbon

Selecting the fish for ^{14}C analysis via AMS resulted in twelve canary rockfish otoliths with estimated birth dates ranging from 1945 to 1980 (Table 4). Collection years ranged from 1991 to 1998, with age estimates of 11 to 49 yr. The choice of available otoliths was designed to have samples with a range of birth years that encompassed the period of ^{14}C increase (pre-bomb to post-bomb). Extracted mass of core material ranged from 3.6 to 7.3 mg, well below the weight of a one year juvenile otolith. The measurement of $\Delta^{14}C$ from this series of otolith cores ranged from -113.1 ± 4.6‰ to 81.9 ± 3.8‰ for the birth years 1945 and 1967, respectively.

Plotting the $\Delta^{14}C$ data with the two reference time series (yelloweye rockfish and Pacific halibut) revealed a strong conformance for the canary rockfish data (Figure 3). Pre-bomb $\Delta^{14}C$ levels for the series of samples with estimated birth years 1945 to 1956 had an average of -105 ± 8‰, similar to the pre-bomb time series for the yelloweye rockfish (-102 ± 9‰) and Pacific halibut (*ca.* -107 ± 7‰). The time of first rise in $\Delta^{14}C$ for the canary rockfish record appears to be between 1957 and 1961, or as late as 1963, as was subjectively determined by visual examination of the plot. Application of the exponential fit method provided an objective means of determining the year of initial rise from pre-bomb levels. The fitted curve (Y = -115.06 + 1.414E-154*exp(0.183*X)) and time of intersection with the 2 SD criterion (*ca.* $\Delta^{14}C$ = -89) indicated the first rise in ^{14}C was 1958. This finding was in agreement with both reference time series and more typical of the yelloweye rockfish distribution. The rapid increase in ^{14}C from 1961 ± 2 yr to a maximum at 1967 ± 2 yr is also in agreement with both reference time series. The peak and post-bomb $\Delta^{14}C$ levels of the canary rockfish more closely resemble the yelloweye rockfish distribution, although the peak $\Delta^{14}C$ level was greater.

A minimum age or lifespan was determined based on the difference between collection year and the estimated birth year for last sample with pre-bomb $\Delta^{14}C$ levels. Because the year of first rise in ^{14}C was calculated as 1958 at a $\Delta^{14}C$ level of -89‰, the last sample to contain levels below this value was the sample with an estimated birth year of 1954 ± 3 yr sample (-104.5 ± 3.2). Based on the difference from collection year (1998) the age of this fish was at least 39 ± 2 yr and the findings support a break-and-burn based age estimate of 44 ± 3 yr for this sample. In addition, assuming the rise of bomb-produced $\Delta^{14}C$ levels up to peak values can also be used as a potential measure of bias, it was further concluded that there was no evidence for ageing bias that was greater than the age estimate precision for the fish aged 31 ± 2 yr to 38 ± 2 yr.

DISCUSSION

Lead-radium dating

The lead-radium dating sample series illustrated a close conformance to the expected lead-radium ingrowth curve with minor exceptions. These data provided general support for ages up to about 50-60 years based on the trend. Because some of the old age groups were approaching the asymptote of the ingrowth curve, small changes in the $^{210}Pb{:}^{226}Ra$ ratio resulted in a higher degree of uncertainty. While the upper limit was not well defined, there was 95% confidence that the oldest canary rockfish used in this study were at least 53 years of age. These findings provide support for 1) canary rockfish age estimation procedures used by DFO and for 2) lifespan estimates exceeding 80 yr based on a continued adherence to the age estimation protocol.

The measured $^{210}Pb{:}^{226}Ra$ activity ratios conformed well to the ingrowth curve for total sample age. Note that the total age of the 3 yr age group was in close agreement with the expected $^{210}Pb{:}^{226}Ra$ activity ratio for a total age of 14 yr. This is an indication that the extracted otolith continues to function as a closed system after removal from the fish and that the initial uptake of exogenous ^{210}Pb was negligible. Findings of this kind, coupled with studies directed at testing for intermediate isotope loss or exogenous incorporation of ^{210}Pb (i.e., Baker et al. 2001, Kastelle and Forsberg 2002), continue to refute concerns about violations to the closed system assumption (e.g., Gauldie and Cremer 2000).

Bomb radiocarbon

The conformity of the canary rockfish ^{14}C record in the present study with the yelloweye rockfish and Pacific halibut $\Delta^{14}C$ reference time-series was compelling information that supported the age estimates and current age estimation procedures. Considering the similarity of biology, ecology, and distribution of the two rockfishes, the use of the yelloweye rockfish $\Delta^{14}C$ time-series as a means of temporal calibration for the canary rockfish record was well supported. Unlike the quillback rockfish, which has a more nearshore distribution as larvae, the canary rockfish $\Delta^{14}C$ record for the period beyond the post-bomb peak was also similar to the yelloweye rockfish time-series. The timing of the initial rise in $\Delta^{14}C$ for canary rockfish otoliths (1957 ± 2 yr) was consistent with the yelloweye rockfish record (1958 ± 2 yr). In addition, it was further concluded that there was no evidence for ageing bias that was greater than the age estimate precision for fish aged 31 ± 2 yr to 38 ± 2 yr because no phase shift was documented in the samples aged as having birth years between the first rise to peak of $\Delta^{14}C$ levels. It is reasonably certain that the samples with pre-bomb $\Delta^{14}C$ levels in core material from otoliths collected in 1998 were at least 39 ± 2 yr and that a minimum estimate of lifespan was 44 ± 3 yr was supported by the measured $\Delta^{14}C$ in the first pre-bomb sample.

Regional pre-bomb $\Delta^{14}C$ levels in the mixed layer of the ocean are assumed to be relatively constant; however, variation in these levels may introduce uncertainty into age validation studies because baseline levels provide the reference for the time of first rise. Pre-bomb levels of ^{14}C and the degree of variation were similar between the canary rockfish and the reference time series (yelloweye rockfishes and Pacific halibut) and considered together (samples with birth dates prior to 1957) provide a mean pre-bomb $\Delta^{14}C$ value of -105 ± 8‰ (n = 23). Adding the results from the quillback rockfish study (Kerr et al. 2005) provided a grand mean $\Delta^{14}C$ of -104 ± 10‰ (n = 26) for the Gulf of Alaska region. This value included samples ranging from the west coast of Vancouver Island, British Columbia, Canada to the northern Gulf of Alaska. To consider this value a characteristic of the regional $\Delta^{14}C$ average during the pre-bomb period (est. 1940 to 1956 from the range of estimated birth years), the biggest assumption is some degree of regional specificity for the ontogeny of each fish sampled. For the Pacific halibut samples, five samples were from young of the year fish that experienced a pelagic phase of up to six to seven months and six samples were 3 to 5 yr fish (cored to the first year) that would have experienced the pelagic phase and possibly a migration period (Piner and Wischniowski 2004). Rockfishes are known to have a pelagic larval stage as well, but the potential complication for using these data as regional indicators of ^{14}C is potential movement over great distances as an adult.

Ontogenetic movement of rockfishes varies considerably among species; many are relatively residential and some can travel great distances (see Love et al. 2002 for a synopsis). The species considered here are not known to move great distances. Tagged yelloweye rockfish off Depoe Bay were residential while at liberty for up to 739 days; however, of the 23 tagged canary rockfish returns off Oregon some were residential and 14 exhibited movement of more than 100 km north or south to a maximum of 236 km from the release location (DeMott 1983; Bill Barss, Oregon State University (*emeritus*), personal communication). This degree of movement, given it may apply to the other species considered here, could broaden the apparent range for the regional mean pre-bomb $\Delta^{14}C$ levels exhibited by these species.

The level of natural pre-bomb $\Delta^{14}C$ ranged from -76.9‰ to -120.0‰, for the four species of Gulf of Alaska fishes. This level of variation could affect the temporal distribution of the bomb signal. An example of how low $\Delta\ ^{14}C$ values can be in the nearshore waters of region was from pre-bomb levels that ranged well below -120‰ off Adak Island, Alaska as evidenced by the study of an alga (*Clathromorphum nereostratum*) that resided at a depth of 10 m (Frantz et al. 2005). A deep water ^{14}C record measured from red tree coral (*Primnoa pacifica*, syn. *P. resedaeformis*) from 263 m in the Dixon Entrance, southeastern Alaska indicated levels can be quite depleted (-129.8 to -136.4‰; A. Andrews, unpublished data). Thus, deep water sources advected to nearshore waters can affect the shape and apparent timing of the first rise in $\Delta^{14}C$, resulting in a vertical attenuation of the bomb signal. This factor provides a reasonable explanation for what appears to be a phase lag of a few years for some samples in the yelloweye and canary rockfish records, but can also be explained by small variations in age interpretation, as is indicated by the error bars.

A recent study, which also used bomb $\Delta^{14}C$ as a tool for age validation, of canary rockfish collected off Oregon provided results that differ from the current study in the timing and magnitude of ^{14}C rise (Piner et al. 2005). Pre-bomb levels off Oregon were similar to the levels reported in this study (-105 ± 8‰), based on four samples with estimated birth years ranging from 1949 to 1956 (*ca.* -103 ± 4‰); however, post-bomb levels appear to have increased more gradually and many samples appear to have a significant phase lag of up to 7 years (average 2-3 yr). In addition, the post-bomb peak values appear to be much lower than recorded for the canary rockfish taken off Canada (30.0 ± 3.5‰ *cf.* 78.5 ± 4.3‰). As stated above with regard to natural variability in pre-bomb $\Delta^{14}C$ levels, it is possible that some of the phase lag in the Oregon canary rockfish study was due to this effect, but it is unlikely that it could be responsible for the low values with rather large apparent phase lags. For example, an apparent lag of 7 years relative to the time of first rise in $\Delta^{14}C$ would require depressions of peak $\Delta^{14}C$ levels on the order of 100‰.

Further examination of the data from the Oregon canary rockfish study revealed that age interpretation alone can explain most of the unexpected distribution, as was discussed by the authors (Piner et al. 2005). Two or three age estimates were listed by Piner et al. (2005) for each sample. They chose to use the first reads in their analyses because the first reads were made following methodologies used in stock assessments (Crone et al. 1999, Methot and Piner 2002); however, the second and/or third reads tended to be older (with differences up to 4 years), and when the oldest age determinations were used many of the critical samples in the unexpected distribution were shifted further toward what would be expected in comparison to the yelloweye rockfish and Pacific halibut records (e.g., highest $\Delta^{14}C$ value at 1967 *cf.* 1970; see Figure 4). Hence, it is likely that the timing of the rise in $\Delta^{14}C$ was closer to 1959-1962 than was depicted in Piner et al. (2005). This finding implies that the later otolith readings were more accurate and an inter-calibration between DFO and ageing laboratories in the USA is recommended. It can be surmised that the study validated a level of age estimate imprecision to an average of about 2.8 years based on the observed phase shift (Piner et al. 2005). When considering this level of age estimate imprecision, it is also possible that the unexpectedly low $\Delta^{14}C$ peak value (30.0 ± 3.5‰) can be attributed to a lack of fish young enough to capture the regional peak $\Delta^{14}C$ level.

Given pre-bomb levels were not more depressed for the Oregon canary rockfish record, it is unlikely that oceanography off Oregon was drastically different in terms of $\Delta^{14}C$ circulation from regions of upwelling further north in the Gulf of Alaska. In support of this hypothesis, the range of pre-bomb $\Delta^{14}C$ values available from all fish records for the northeastern Pacific Ocean was -76.9‰ to -120.0‰ with an overall average of -103 ± 9‰ (Figure 5). In addition, a recent study of cowcod (*Sebastes levis*) otoliths from off Southern California provided a measure of pre-bomb levels much further south with a mean of -97 ± 3‰ (n = 4; A.H. Andrews, unpublished data). Less depleted $\Delta^{14}C$ values for more southerly coastal waters of the northeastern Pacific Ocean have been attributed to less influence from upwelling (Ingram and Southon 1996). The unexpectedly low levels for post-bomb measurements in the study of canary rockfish off Oregon are difficult to explain in these terms and more suggestive of age estimation problems.

Conclusions

The findings of this study provided robust support for canary rockfish age estimates. Lead-radium dating proved successful by showing conformance to the expected lead-radium ingrowth curve and provided support for ages up to about 50-60 years. At the very least, there was 95% confidence that lead-radium dating determined a minimum lifespan of 53 years, discounting early lifespan estimates on the order of 20 yr. These findings were further supported by $\Delta^{14}C$ data that indicated canary rockfish have a minimum lifespan of at least 44 ± 3 years. In addition, the conformity of $\Delta^{14}C$ measurements from otolith cores with estimated birth years for the post-bomb era provided further support for these age estimates down to about 30 years. To differing degrees, both techniques provided support for the age estimation procedures used in routine age assignments for canary rockfish by the DFO Ageing Lab and an age validated basis for inferring that canary rockfish can live more than 80 years.

The investigation of pre-bomb $\Delta^{14}C$ levels in the mixed layer of the Gulf of Alaska from regional fish otolith records resulted in a mean $\Delta^{14}C$ of -104 ± 10‰ (n = 26) with a potential range of -76.9‰ to -120.0‰. This relatively high degree of regional variability in pre-bomb levels would have had a natural effect on the apparent timing of the first rise in $\Delta^{14}C$ and may provide a reasonable explanation for what appears to be a phase lag of a few years for some samples. When considering all fish studies ranging from Southern California to the Gulf of Alaska, including cowcod and the five oldest Oregon canary rockfish samples (Piner et al. 2005), a grand mean $\Delta^{14}C$ of 103 ± 9‰ (n = 35) was calculated. Based on this observation the levels for pre-bomb $\Delta^{14}C$ in the mixed layer were fairly constant in a much broader regional context.

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Table 1. List of attributes for each canary rockfish sample (age group) collected off British Columbia, Canada that was analyzed using lead-radium dating.

Sample number	Average age and range (yr)	Fork length and range (cm)	Average collection date and range	Core number Male/Female
CR1	3 (3)	19.1 (19-21)	5/91	16[1]
CR2	10 (10)	38.6 (33-46)	6/21/91 (6/14/91-7/15/91)	8/10
CR3	18.8 (18-20)	53.2 (44-58)	3/21/91 (2/13/91-6/14/91)	11/9
CR4	52.2 (51-54)	53.7 (51-56)	12/12/94 (7/14/93-10/14/95)	20/0
CR5	52.0 (50-54)	52.5 (51-55)	9/8/90 (4/14/90-11/13/90)	6/0
CR6	11 (11)	45.0 (40-48)	3/5/91 (2/13/91-3/15/91)	3/3
CR7	41.0 (40-42)	54.0 (49-57)	3/19/98 (2/12/98-4/14/98)	8/0
CR8	45.3 (45-46)	54.1 (52-59)	3/28/98 (3/15/98-4/14/98)	5/2
CR9	55.4 (55-56)	53.2 (50-55)	3/15/98 (2/12/98-4/14/98)	5/0
CR10	3 (3)	19.9 (19-21)	5/91	16[1]
CR11	51.8 (50-53)	55.2 (52-57)	3/15/98 (2/12/98-4/14/98)	6/0
CR12	53.6 (53-54)	54.4 (52-57)	5/3/98 (2/12/98-11/13/98)	4/1

[1] Immature fish

Table 2. Radiometric results for canary rockfish sample series. Listed are the estimated age range from growth-zone counts and measured ^{210}Pb and ^{226}Ra activities for all samples, except where ^{226}Ra was not recovered (N.R.). Two standard errors were expressed as an error percentage for the measured activities. Calculated activity ratios and the corresponding margin of error (based on error propagation and the delta method) are given to provide a 95% confidence interval.

Sample number	Age group (yr)	A ^{210}Pb (dpm g^{-1}) ± % error	A^{226}Ra (dpm g^{-1}) ± % error	^{210}Pb:^{226}Ra activity ratio
CR1	3	0.0381 ± 6.9	N.R.	N.A.[1]
CR2	10	0.0377 ± 6.2	N.R.	N.A.[1]
CR3	18-20	0.0760 ± 4.9	N.R.	N.A.[1]
CR4	51-54	0.0727 ± 5.3	N.R.	N.A.[1]
CR5	50-54	0.0797 ± 7.2	0.0899 ± 6.4	0.866 (0.085)
CR6	11	0.0478 ± 8.5	0.102 ± 4.3	0.470 (0.045)
CR7	40-42	0.0806 ± 6.8	0.106 ± 13.9	0.761 (0.118)
CR8	45-46	0.0942 ± 6.7	0.109 ± 8.0	0.863 (0.090)
CR9	55-56	0.0632 ± 7.8	0.0924 ± 8.6	0.684 (0.080)
CR10	3	0.0396 ± 9.5	0.122 ± 6.1	0.326 (0.037)
CR11	50-53	0.0726 ± 7.7	0.0803 ± 1.3	0.904 (0.071)
CR12	53-54	0.0707 ± 7.4	0.0888 ± 3.8	0.795 (0.066)

[1] Not applicable (N.A.) because the activity of ^{226}Ra was highly variable and precluded use of an average.

Table 3. Summary of growth-zone ages and radiometric ages for canary rockfish age groups. Average growth-zone age (CV of 5.8% relative to the mean) are given with radiometric age calculated from the measured ^{210}Pb:^{226}Ra activity ratios and corrected for time since capture. Radiometric age range was based on the analytical uncertainty and error propagation (2 SE).

Sample number	Age group (yr)	Average growth-zone age (yr)	Radiometric age range (yr)
CR5	50-54	52 (2.9)	59 (41-103)
CR6	11	11 (0.6)	10 (8-13)
CR7	40-42	41 (2.3)	43 (30-65)
CR8	45-46	45 (2.5)	61 (44-95)
CR9	55-56	55 (3.1)	34 (27-43)
CR10	3	3 (0.1)	3 (1-4)
CR11	50-53	52 (2.9)	71 (53-114)
CR12	53-54	54 (3.0)	47 (38-60)

Table 4. Summary of fish age and otolith data for canary rockfish collected off British Columbia, Canada. Resolved age was the final age estimate assigned by DFO. Birth year was the collection year minus the resolved age. Age error was the uncertainty associated with the age estimate (CV = 5.8%). Radiocarbon values from the otolith cores of canary rockfish were expressed as $\Delta^{14}C$ with the AMS analytical uncertainty (SD).

Resolved age (yr)	Collection year	Birth year (± 5.8% CV)	Core sample weight (mg)	$\Delta^{14}C$ (‰) ± SD
49	1994	1945 ± 3 yr	5.8	-113.1 ± 4.6
48	1998	1950 ± 3 yr	3.6	-97.3 ± 3.1
44	1998	1954 ± 3 yr	5.2	-104.5 ± 3.2
41	1998	1957 ± 3 yr	7.3	-88.6 ± 3.2
38	1998	1960 ± 2 yr	6.3	-96.4 ± 3.3
37	1998	1961 ± 2 yr	4.4	-84.3 ± 3.1
35	1998	1963 ± 2 yr	8.6	-61.8 ± 3.2
33	1998	1965 ± 2 yr	4.4	50.2 ± 4.6
31	1998	1967 ± 2 yr	5.6	81.9 ± 3.8
22	1991	1969 ± 1 yr	5.1	62.0 ± 3.8
18	1991	1973 ± 1 yr	5.4	34.6 ± 3.6
11	1991	1980 ± 1 yr	6.0	18.0 ± 3.8

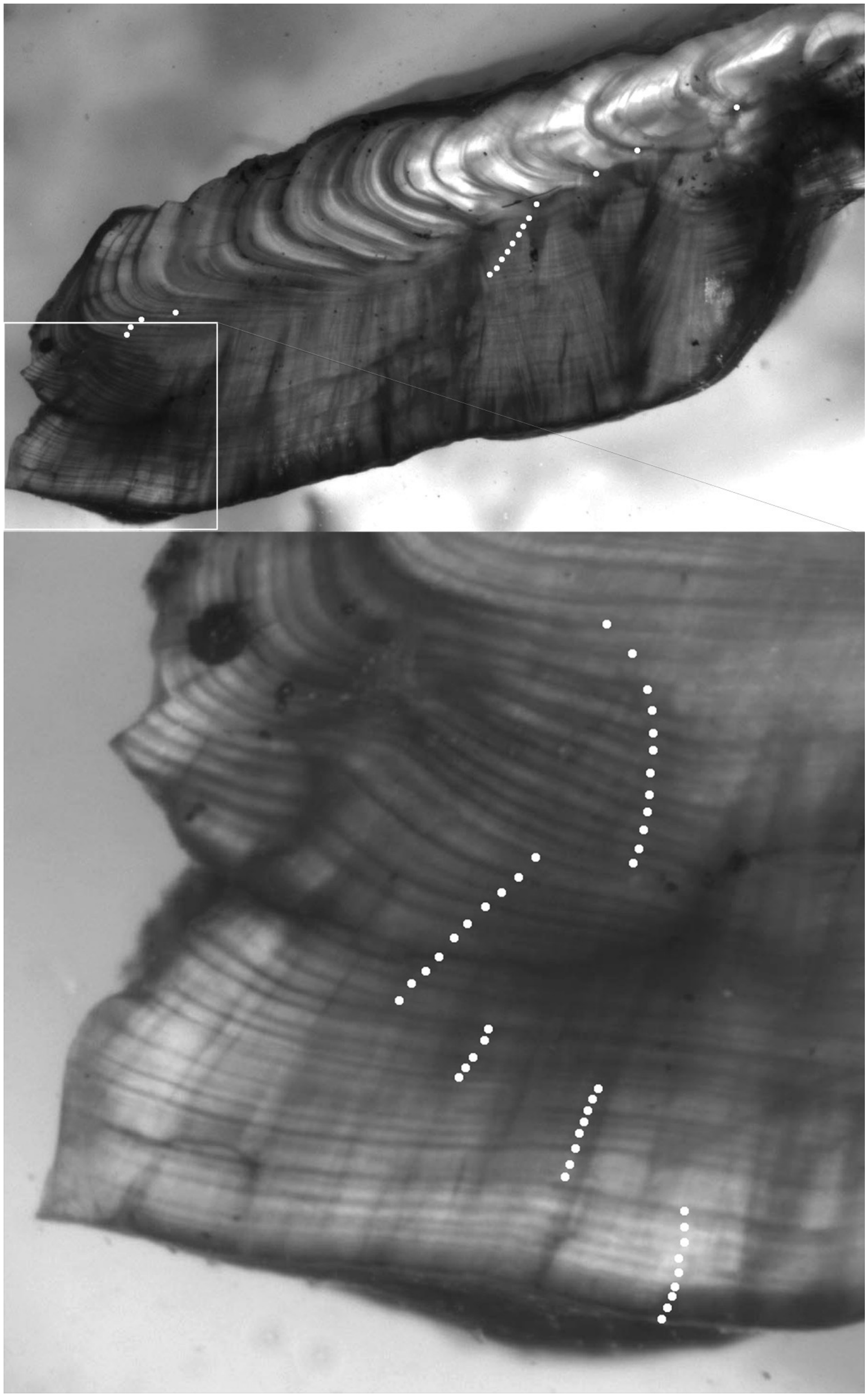
Figure 1. Pictured is an example of an aged canary rockfish otolith using the burnt otolith section technique at the DFO Ageing Lab. Marked are the zones assumed to represent annual growth that are counted during routine age estimation. The estimated age of this section was 60 years.

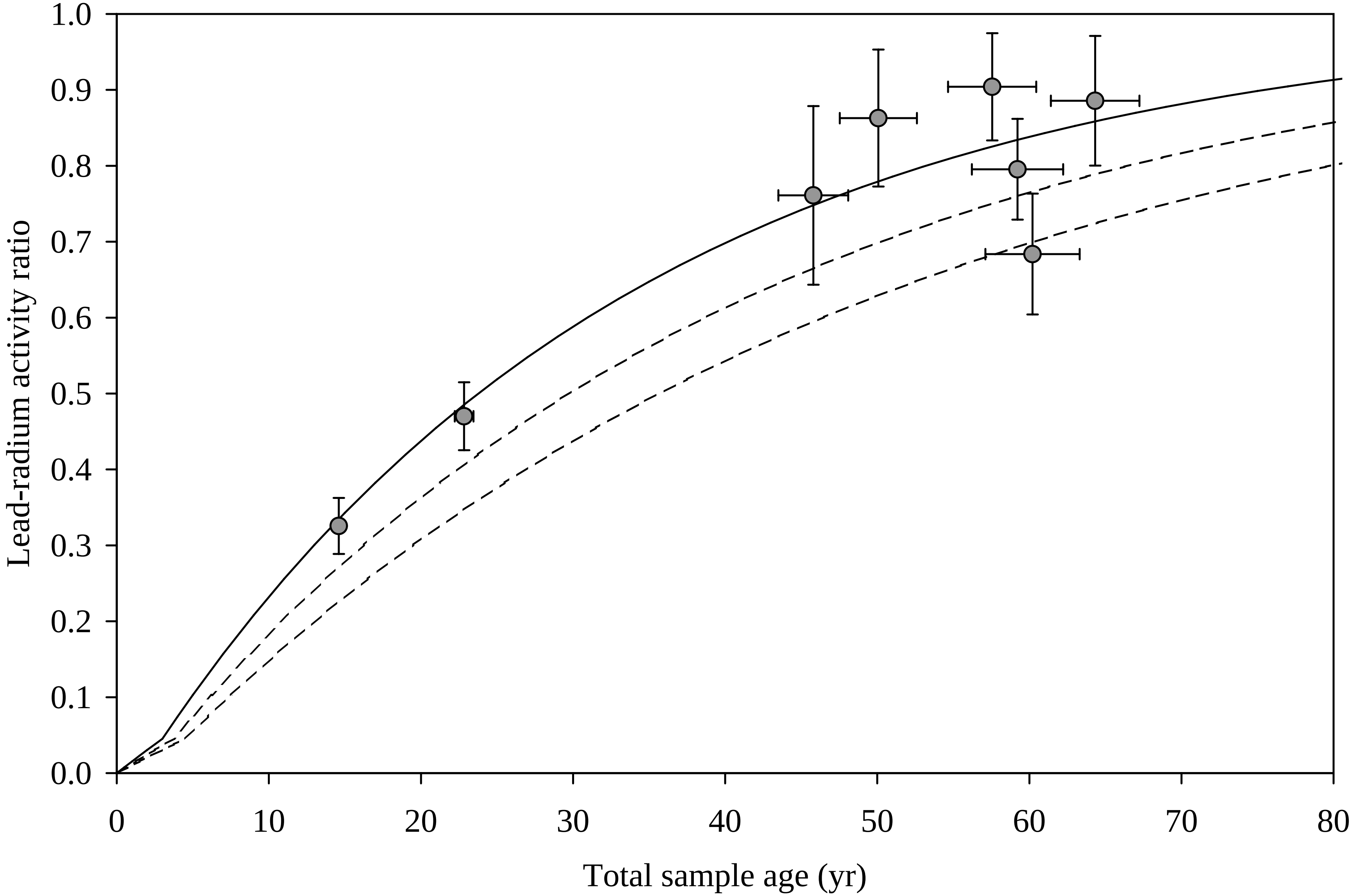
Figure 2. Plot of the measured ^{210}Pb:^{226}Ra ratios with respect to total sample age (growth-zone age plus the time since capture) for canary rockfish samples, plotted with the ^{210}Pb:^{226}Ra ingrowth curve. Horizontal error bars (some within the symbol size) represent age estimate uncertainty (CV = 5.8%) relative to the mean growth-zone age. The vertical error bars represent the analytical uncertainty associated with measuring ^{210}Pb and ^{226}Ra (2 SE). Dashed lines below signify the affect of age estimate bias for over estimation of age (b = 25% and b = 50%).

Figure 3. Plot of measured $\Delta^{14}C$ values for the canary rockfish otoliths with respect to estimated birth year, derived from growth zone counts determined by DFO. The horizontal bars represent the range of possible birth dates from the age estimate uncertainty (CV = 5.8%). Note the strong conformity of the canary rockfish data with the yelloweye rockfish and Pacific halibut reference time series.

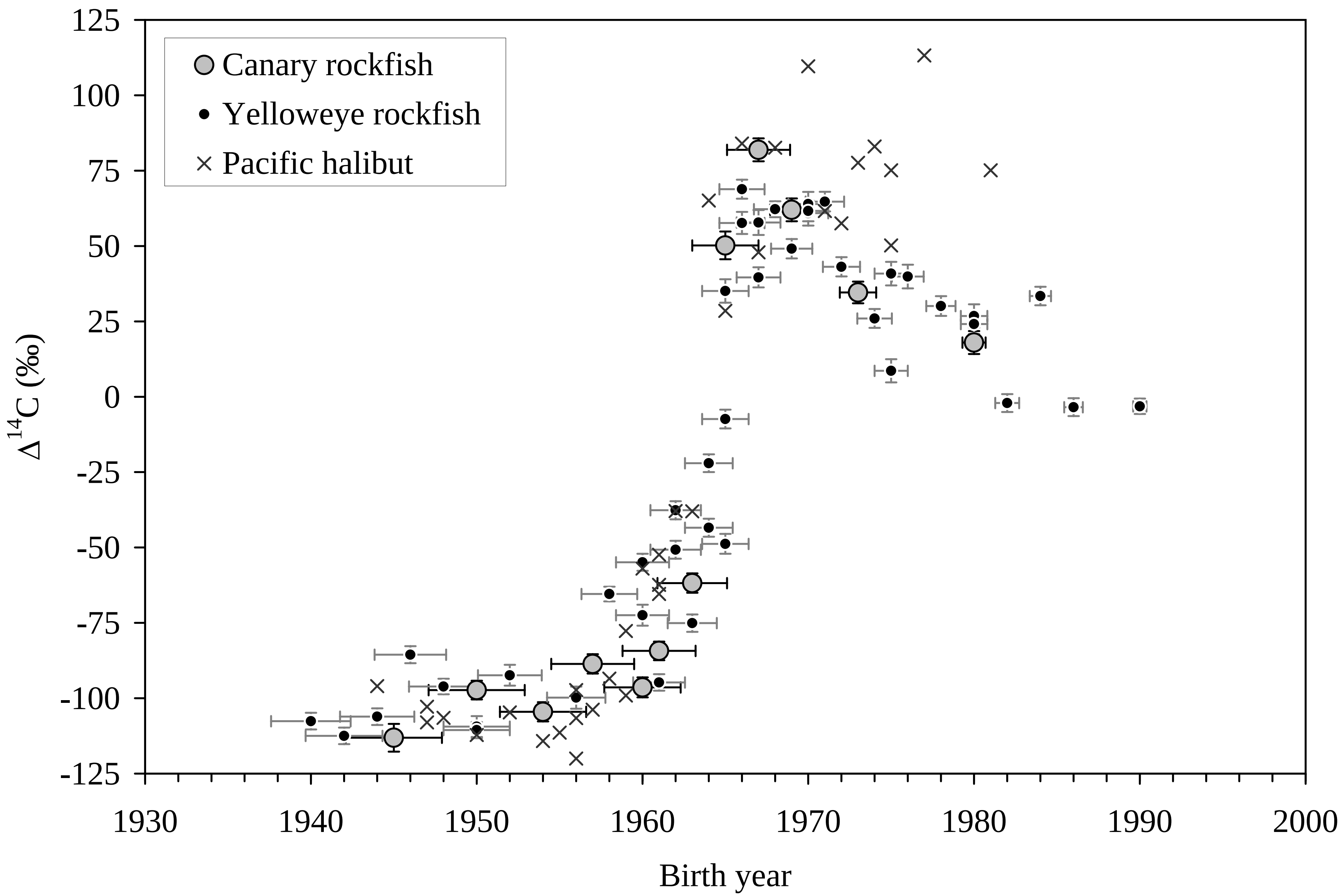
Figure 4. Plot of data taken from Piner et al. (2005) for canary rockfish collected off Oregon with data from this study and the yelloweye rockfish reference time-series. The birth dates for the Oregon canary rockfish, in this case, have been plotted with alternate birth years calculated from other age interpretations listed in the study (Piner et al. 2005). This figure is provided to illustrate that the findings for Oregon canary rockfish may have been better than initially interpreted and that the second and third otolith reads in the study were probably more accurate.

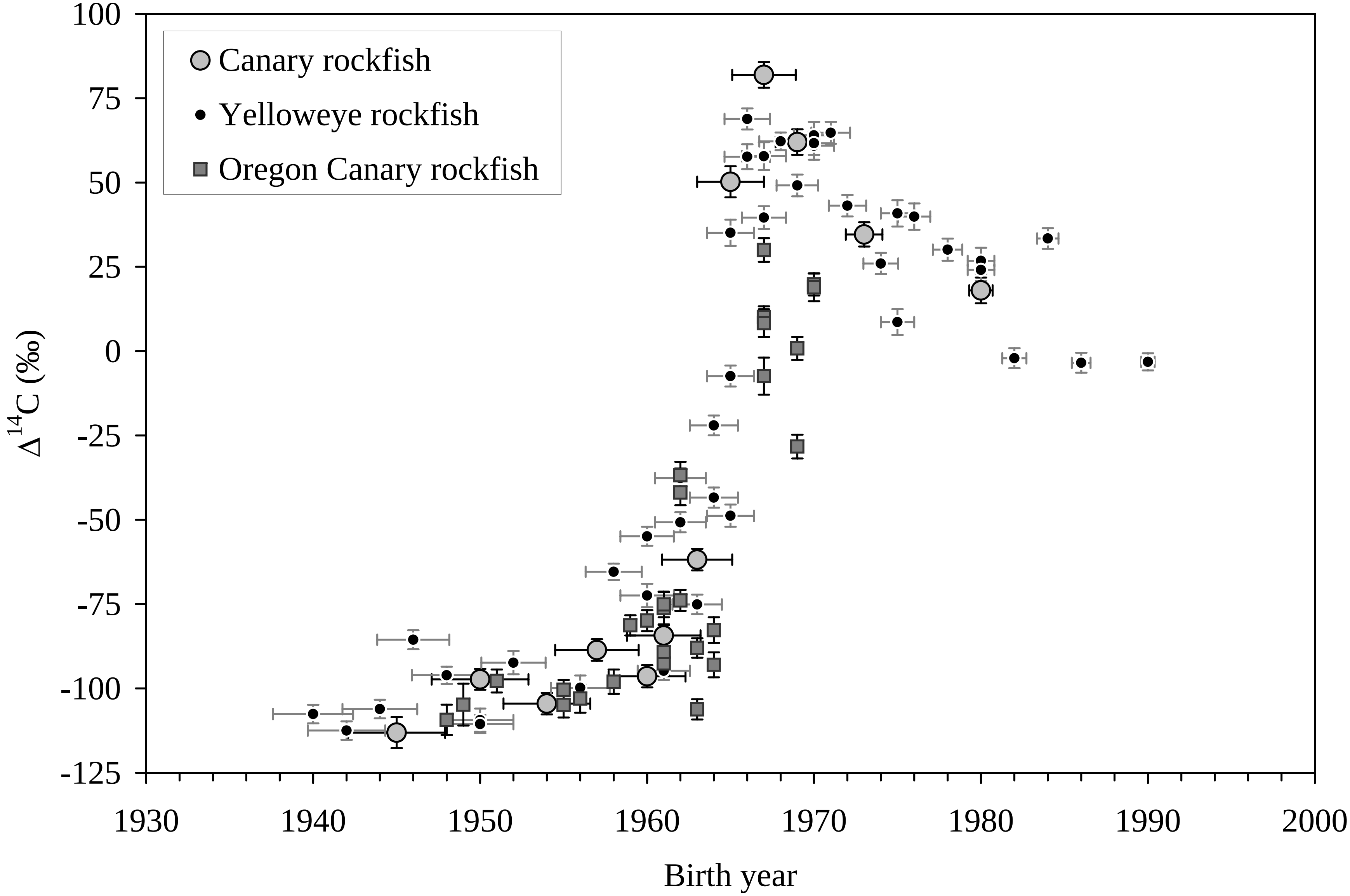
Figure 5. Average pre-bomb $\Delta^{14}C$ from fish otolith records throughout the northeastern Pacific Ocean. Species and associated values are placed central to the region samples were taken. All samples were from coast and shelf waters along the Gulf of Alaska to the California coast. The value for Pacific halibut is placed as such because the samples ranged from off Kodiak Island, Alaska to Vancouver Island, British Columbia, Canada.



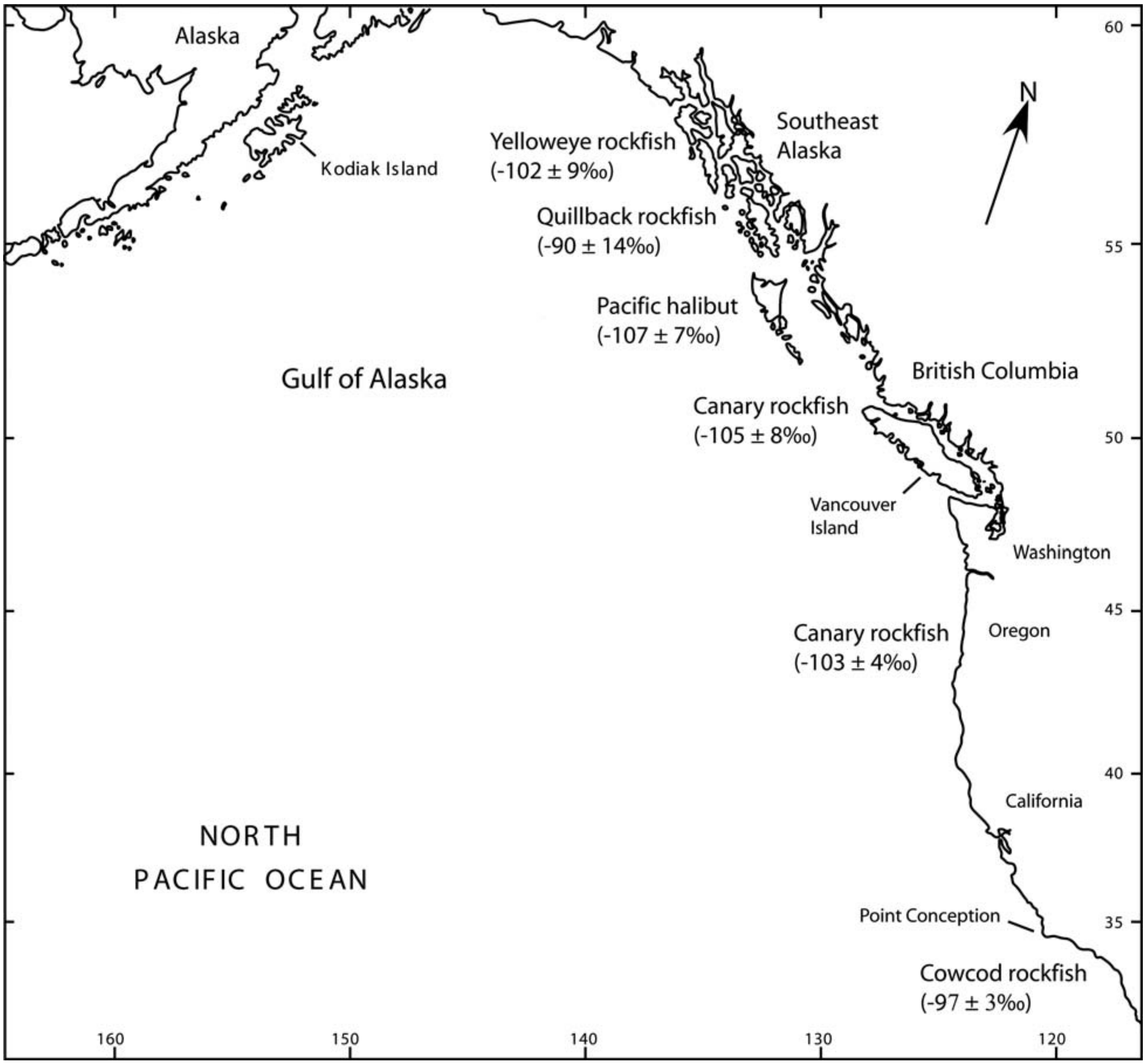


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Lead-radium activity ratio
0
10
20
30
40
50
60
70
80
Total sample age (yr)


Canary rockfish
Yelloweye rockfish
Pacific halibut
125
100
75
50
25
0
-25
-50
-75
-100
-125
Δ14C (‰)
1930
1940
1950
1960
1970
1980
1990
2000
Birth year



Canary rockfish
Yelloweye rockfish
Oregon Canary rockfish
100
75
50
25
0
-25
-50
-75
-100
-125
Δ14C (‰)
1930
1940
1950
1960
1970
1980
1990
2000
Birth year


Alaska
Kodiak Island
Yelloweye rockfish
(-102 ± 9‰)
Southeast
Alaska
Quillback rockfish
(-90 ± 14‰)
Pacific halibut
(-107 ± 7‰)
Gulf of Alaska
British Columbia
Canary rockfish
(-105 ± 8‰)
Vancouver
Island
Washington
Canary rockfish
(-103 ± 4‰)
Oregon
California
NORTH
PACIFIC OCEAN
Point Conception
Cowcod rockfish
(-97 ± 3‰)
N
60
55
50
45
40
35
160
150
140
130
120